

Proposal for an electron polarimeter a luminosity monitor and a low Q^2 -tagger

Polarimeter and Luminosity Detector Working Group

BNL-Physics: Elke-Caroline Aschenauer, Alexander Kiselev, William Schmidke

BNL-CAD: Vladimir Litvinenko , Brett Parker, Vadim Pitsyn, Dejan Trbojevic and the eRHIC Machine Design Group

Byelorussian State University: Vladimir Makarenko

Cracow University of Technology: Janusz Chwastowski

1 Introduction

To be able to realize the physics program as described in the EIC White paper [1] an electron ion collider has to fulfill the following criteria:

- Luminosity on the order of $10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ and higher
- Flexible center of mass energies
- Electrons and protons/light nuclei (He^3 or D) highly polarized ($>60\%$)
- Wide range of nuclear beams (d to U)
- Wide angular acceptance through the IR for protons from exclusive reactions and neutrons from nuclear breakup in the outgoing proton beam direction
- Wide angular acceptance through the IR for photons from bremsstrahlung and leptons from low Q^2 -process in the outgoing lepton beam direction

The two proposals to realize an EIC are built on two very different machine designs. The JLab proposal is based on a ring-ring design with a rep-rate of 1 ns. The BNL proposal is based on an energy-recovery linac for the lepton beam, which is colliding with the hadron beams in the existing RHIC complex.

Because of the high luminosity at an EIC, systematic effects will limit the precision of most measurements. This puts very high requirements on the statistical precision of the luminosity and polarization measurement as well as on their systematic uncertainties.

As an example we show the impact of systematic uncertainties on the determination of the gluon polarization $\Delta g(x, Q^2)$ [2] by measuring the double spin asymmetry $A_{||}(x, Q^2)$ which is proportional of the ratio of the polarized and unpolarized structure function $g_1(x, Q^2)$ and $F_1(x, Q^2)$. Even though the DIS structure function g_1 probes mainly the sum of quark and antiquark parton distribution functions (PDF), its scaling violations at small enough values of x are approximately related to the polarized gluon density, $\frac{dg_1(x, Q^2)}{d \ln Q^2} \sim -\Delta g(x, Q^2)$ (1.1). A full QCD analysis has been performed using EIC pseudo data for inclusive and semi-inclusive double spin asymmetries.

Figure 1 shows the impact of systematic and statistical uncertainties vs. only statistical uncertainties in the determination of the integral contribution of the gluons on the total spin of the proton. A total systematic uncertainty on the order of 2% would be important to achieve to profit from the statistical precision available at an EIC. With the low- x double spin asymmetries being on the level of 10^{-4} , this will require measuring the relative luminosity to $\sim 10^{-5}$.

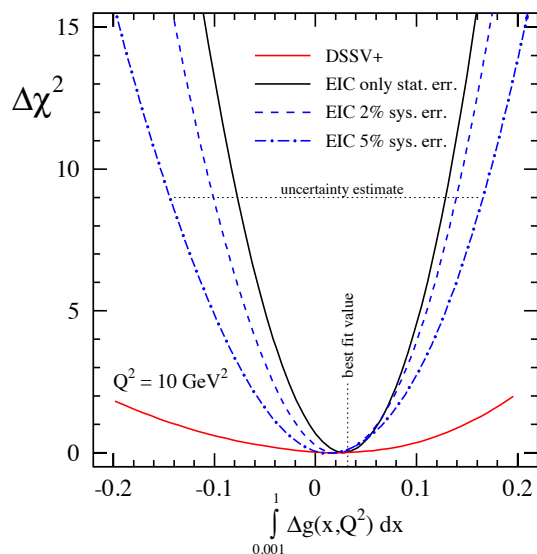


Figure 1: χ^2 profiles for the first moments of the gluon truncated to the region $0.001 < x < 1$. The results are based on using current data (DSSV+) and sets of projected EIC data with two different c.m.s.-energies (5GeVx100GeV and 5GeVx250GeV). The χ^2 profiles assuming only statistical uncertainties and adding 2% and 5% systematic uncertainty in the fit, solid, dotted and dot-dashed lines, respectively.

For several physics measurements, e.g. the polarized and unpolarised photon structure it will be important to measure Q^2 of the event significantly below 1 GeV^2 . Current preliminary detector designs foresee to measure Q^2 up to $\sim 0.1 \text{ GeV}^2$ in the main detector, but to reach to $Q^2 < 0.1 \text{ GeV}^2$ the scattered lepton needs to be detected in a so-called low Q^2 -tagger. Such a device would normally consist of an electromagnetic calorimeter several meters downstream of the IR, typically after a dipole magnet, which would function to filter the scattered leptons with energies close to the beam energy and small p_t from the core of the beam.

2 Details about the Polarimeter Detector Design and Simulations

Compton backscattering of laser photons has been used to measure lepton beam polarization at HERA [4] and other facilities. Unlike the HERA electron synchrotron, each bunch in an eRHIC ERL would pass only once through the interaction region. This requires control and monitoring of bunch-to-bunch fluctuations of both intensity and polarization. For example, the Gatling gun polarized electron source [3] has several cathodes, which may have significant variations among the cathodes. Also, the question arises at which point during the bunches single pass through the ERL to measure polarization. A list of significant challenges to polarization measurements include:

- Fluctuations in polarization from cathode to cathode in the Gatling gun
 - Jlab experience [5] shows that for SVT superlattice photocathodes, it's not uncommon to see the polarization vary from $\sim 83\%$ to 88% , from one photocathode to the next, so $\sim 85\%$ polarization $\pm 3\%$ for wafer to wafer. A typical plot of polarization vs. wavelength for a SVT wafer is shown in **Error! Reference source not found.** (left). At CEBAF the wavelength of the laser is not varied, but fixed at 780nm . It is possible that the measured 83% polarization would increase to 88% if a different (higher) wavelength would be used. For the eRHIC Gatling gun polarized source an individual laser is foreseen for each individual cathode.
- Fluctuations in bunch current from cathode to cathode
 - Another problem could be a phenomenon called surface charge limit, regularly seen at SLAC. It was thought the Surface Charge Limit was only a problem for high bunch charge beams, but it was also observed at CEBAF even at sub-pC bunch charge. Because of the Space Charge Limit, the quantum-efficiency (QE) is not constant as a function of the laser power. Surface Charge Limit arises when the photocathode is subject to ion bombardment. Figure 2 (right) shows, for a freshly activated waver, more laser power provides more beam current, but at $\sim 300\mu\text{A}$, it becomes harder to increase the current, because the wafer is subjected to more ion bombardment. At this moment the QE falls and it becomes impossible to extract $300\mu\text{A}$, even with infinite laser power. With 20 photocathodes as in the Gatling gun, it could be possible each cathode has a different level of surface charge limit. One photocathode might respond very linearly with laser power, whereas another photocathode might be so damaged, one just can't obtain the wanted bunch charge.
- Polarization losses from the polarized source to full energy.
 - In SLC losses in the arcs have been significant.
 - eRHIC Spin decoherence: The spin rotation angle depends on the particle energy. The energy spread in the beam causes spin decoherence and loss of beam polarization. This effect will influence where one wants to measure polarization in the ring.
- Polarization deterioration during collision
 - A problem discussed intensively for ILC, again this effect influences where one wants to measure polarization in the ring
- Possible polarization profile for the lepton bunches
 - A significant polarization profile in the longitudinal direction can be circumvented using a 352MHz RF [6]

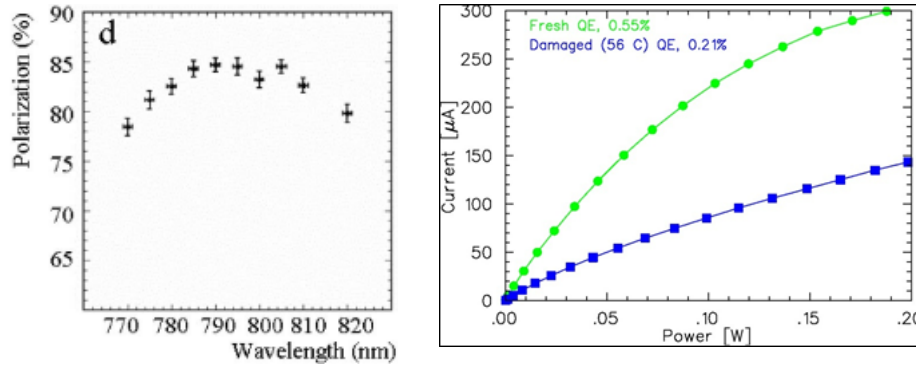


Figure 2: Left: Polarization vs. wavelength for a SVT wafer [5]. **Right:** Bunch current as function of laser power and QE [5].

The current and polarization variations among the cathodes can be straightforwardly addressed by performing both the luminosity and polarization measurements for each cathode separately. These measurements need to be further divided among the approximately 120 RHIC hadron bunches to monitor fluctuations among the bunches.

To address the loss of polarization through a bunch pass through the ERL, an ideal solution is to measure the polarization at the IP. However, during lepton-hadron collisions the backscattered Compton photons would be overwhelmed by the bremsstrahlung photons discussed in the following section. A straightforward way to overcome this is to have empty bunches in the RHIC hadron beam. If the polarimeter laser is fired through the IP on these bunch crossings, the backscattered Compton photons can be measured in the zero degree photon calorimeter of the luminosity system. If the number of source cathodes is not a factor of the number of RHIC bunches (120), lepton bunches from each cathode can pair with an empty RHIC bunch after some number of RHIC revolutions. If the number of source cathodes is a factor of the number of RHIC bunches, a train of empty RHIC bunches equal to the number of cathodes would allow the polarization measurement.

In addition it will be important to understand what are the requirements to obtain a statistically significant polarization number per cathode per time unit to track polarization changes due to variations in the cathode or overall machine performances. This will influence for example, which laser frequency should be used for the polarimeter.

If for some reason, e.g. space limitations, the Compton laser cannot be accommodated at the IP, see Figure 3, the polarimeter system will need to be located before the final bend into the IP or after the first bend out of the IP. This would obviate the need to pair with empty RHIC bunches; however, possible differences between the polarization at the IP and the measurement point would need to be understood through beam simulations. Similarly, possible polarization deterioration through the collision, and polarization profiles, will need to be studied with beam simulations. For the longitudinal beam profile, study is needed to determine if varying the laser beam IP, e.g. through timing shifts, will provide enough resolution to measure a possible polarization profile.

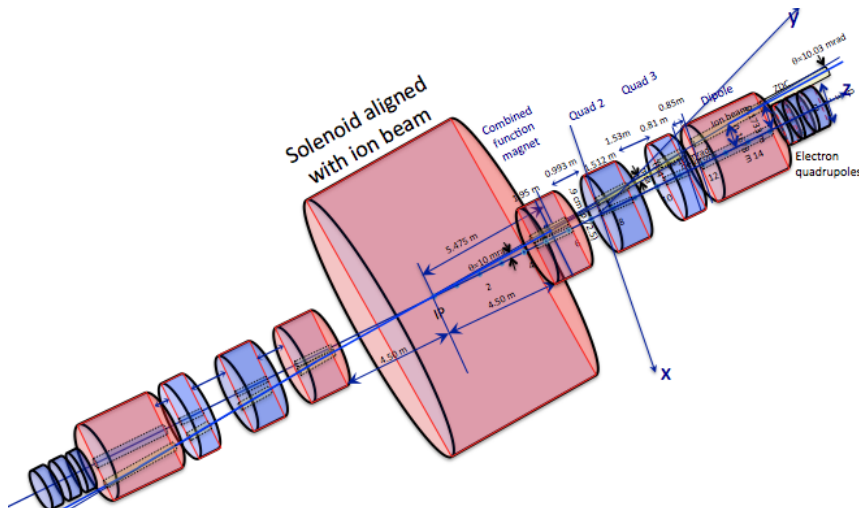


Figure 3: Schematic view of the current eRHIC IR design

3 Details about the Luminosity Detector Design and Simulations

The bremsstrahlung process $ep \rightarrow ep\gamma$ was used successfully for the measurement of luminosity by the HERA collider experiments [citations]. It has the features of a precisely known QED cross-section, and a high rate, which allowed negligible statistical uncertainty. Different from HERA, where only the lepton beam was polarized, in an EIC both the lepton and proton/light ion beams will be polarized. Then the bremsstrahlung rate is sensitive to the polarization dependent term \mathbf{a} in the cross section:

$$\sigma_{\text{brems}} = \sigma_0(1 + \mathbf{a} \cdot \mathbf{P}_e \mathbf{P}_h)$$

Thus, the polarization ($\mathbf{P}_e, \mathbf{P}_h$) and luminosity measurements are coupled, and the precision of the luminosity measurement is limited by the precision of the polarization measurement. This also limits the precision of the measurement of double spin asymmetries $A_{LL} = \frac{1}{P_e P_h} \left[\frac{N^{++/-} - RN^{+-/+}}{N^{++/-} + RN^{+-/+}} \right]$ through the determination of the relative

$$\text{luminosity } R = L^{++/-} / L^{+-/+}.$$

The straightforward method of measuring bremsstrahlung uses a calorimeter at zero degrees in the lepton direction to count the resulting photons, the distribution of which is strongly peaked in the forward direction. The calorimeter is also exposed to the direct synchrotron radiation fan and must be shielded, degrading the energy resolution. At peak HERA luminosities, the photon calorimeters were hit by 1-2 photons per HERA bunch crossing, at which rate pileup effects were already significant. At an EIC luminosity of $10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ the mean number of photons per bunch crossing is over 20. Examples of distributions of energy depositions in such a calorimeter for various mean numbers of photons per bunch crossing are shown in Figure 4. The distributions are broad, with a mean proportional to the number of photons per bunch crossing. The counting of bremsstrahlung photons thus is effectively an energy measurement in the photon calorimeter, with all of the related systematic uncertainties (e.g. gain stability) of such a measurement.

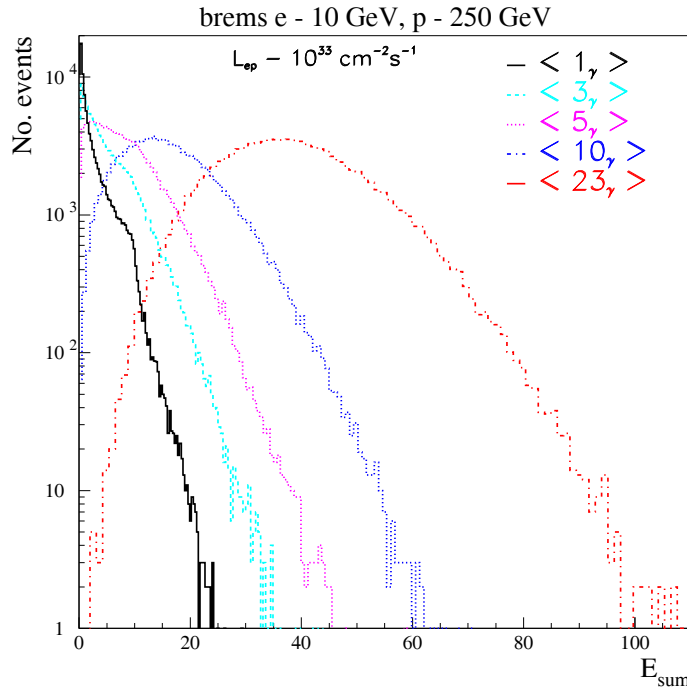


Figure 4: Energy depositions (in GeV) in a zero degree photon calorimeter for various mean numbers of photons per bunch crossing, which is 23 for $L = 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$.

An alternative method of counting bremsstrahlung photons, used with smashing success by the ZEUS collaboration at HERA, employs a pair spectrometer, diagrammed in Figure 5. A small fraction of photons are converted to e^+e^- pairs in the vacuum chamber exit window. A dipole magnet splits the pairs and each particle hits a separate calorimeter adjacent to the unconverted photon direction. This has several advantages over a zero degree photon calorimeter:

1. The calorimeters are outside of the primary synchrotron radiation fan
2. The exit window conversion fraction reduces the overall rate
3. The spectrometer geometry imposes a low energy cutoff in the photon spectrum, which depends on the magnitude of the dipole field and the transverse location of the calorimeters

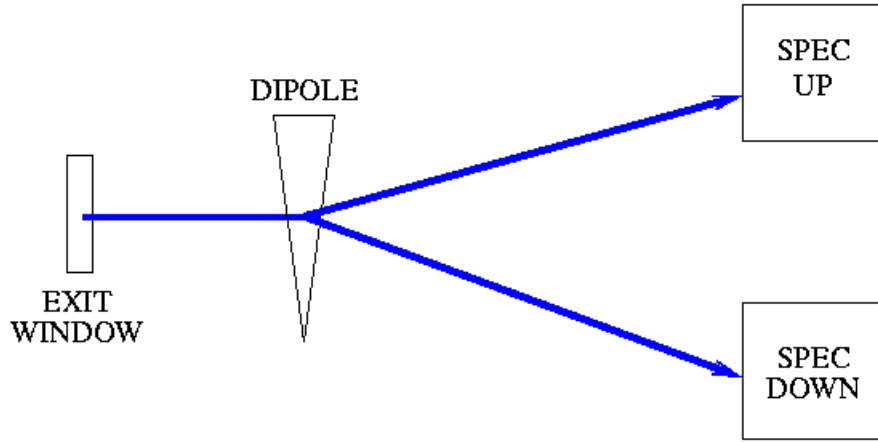


Figure 5: Layout of a pair spectrometer along the zero degree photon beam.

The variable parameters of the last two points (conversion fraction, dipole field and calorimeter locations) may be chosen to reduce the rate to less than or of order one e^+e^- coincidence per bunch crossing even at nominal EIC luminosities. Thus counting of bremsstrahlung photons is simply counting of e^+e^- coincidences in a pair spectrometer, with only small corrections for pileup effects.

At the very highest luminosities considered for the EIC, a pair spectrometer will experience multiple hits per bunch crossing. An important observation is that each spectrometer calorimeter module is hit by e^+e^- in a limited energy range, with energy inversely proportional to the transverse distance between the photon conversion and the impact position in the calorimeter.

If the energy resolution of the calorimeter modules is sufficient to separate single from multiple hits, it would enable monitoring and correction of pileup effects.

The inherent angular distribution of bremsstrahlung photons from a 10 GeV lepton beam is ~ 30 u-rad; this is significantly smaller than the angular divergence from the beam emittance, expected to be ~ 130 u-rad at 10 GeV. Thus the photon distribution centroid measures the beam direction, and the RMS of the distribution provides information on the beam emittance. The zero degree photon calorimeter can provide a sensitive measure of the centroid, but the RMS is significantly decreased because the energy deposits per bunch are a sum from many photons. By contrast, if the pair spectrometer can distinguish single from multiple photon hits, it would provide good measures of both the photon distribution centroid and RMS. This would be a valuable addition to the machine instrumentation, useful for beam operation and tuning.

The design studies of the lumi-monitor will integrate the simulations for the low Q^2 -tagger. Pileup effects due to scattered leptons from the bremsstrahlungs process will make it very difficult to tag the scattered leptons from low Q^2 deep inelastic scattering events.

4 Proposal Deliverables:

The goal of this proposal is to develop an MC program to calculate the bremsstrahlung cross-section dependence on the beam polarizations and on the direction of the hadron beam polarization, longitudinal vs. transverse. Further, this MC should be able to calculate the polarization independent bremsstrahlung cross section for electron-ion collisions.

This MC will be the basis for simulations to design a luminosity monitor, to determine its performance requirements, and to integrate this luminosity monitor in the IR region. Integration from the first stages is extremely critical to optimize the acceptance of the luminosity monitor and keep systematic effects, e.g. due to beam movements, at a minimum. Integrating the luminosity detector into the IR will allow simultaneously studying the feasibility of a low Q^2 -tagger and integrating it into the entire setup.

For the lepton polarimeter part of the proposal the goals are the same, the polarimeter will be integrated in the overall MC describing the detector and the IR of the machine. Further, the detector performance requirements will be determined. We will emphasize providing fast feedback on the polarization for the machine performance as well as providing the best polarization uncertainty for the polarization measurements used by the experiments.

As the integration of the detectors is machine dependent, we would like first to concentrate on the implementation of the detectors into eRHIC. But the MC implementations of the detectors as well as the MC code to simulate the bremsstrahlung cross section will be kept so general that things can be easily transferred to MEIC.

To achieve these goals, we would like to hire a postdoc for 2 years to perform all the simulations and to integrate the luminosity detector, low Q^2 -tagger and the electron polarimeter into the overall detector / IR MC package.

Further it will be essential to invite experts on lepton polarimetry and luminosity measurements in DIS to BNL for collaboration as well as present the results on the relevant conferences in the field.

Work split/assignments:

- IR design: Brett Parker, Dejan Trbojevic and the eRHIC machine design team
- MC to simulate the bremsstrahlungs cross section: Vladimir Makarenko
- Overall Detector and IR MC framework: Alexander Kiselev
- Luminosity detector design and simulations: W. Schmidke, Janusz Chwastowski and new PostDoc
- low Q^2 -tagger design and simulations: E.C. Aschenauer, W. Schmidke and new PostDoc
- Polarimeter detector design and simulations: E.C. Aschenauer, new PostDoc and the eRHIC machine design team

Cost table:

	FY 2014	FY 2015	FY 2016
Cost for PostDoc salary fully burdened	\$62705 (6 month)	\$125,411 (12 month)	\$62705 (6 month)
Cost for travel to invite experts and to go to relevant conferences	5 person-months (incl. 4 flights) \$10k	5 person-months (incl. 4 flights) \$10k	5 person-months (incl. 4 flights) \$10k

References:

- [1] The EIC White Paper “The Next QCD Frontier-Understanding the glue that binds us all” arXiv:1212.1701 (nucl-ex)
- [2] E. C. Aschenauer, R. Sassot, and M. Stratmann, Phys. Rev. D86, 054020 (2012), arXiv:1206.6014
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- [6] V. Pitsyn http://faculty.virginia.edu/PSTP2013/Talks/VP_PSTP13_Talk.pptx